

**Project Title: Characterization of Biodiesel for Use
in Diesel Engines**

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Executive Summary

A single cylinder, naturally aspirated, direct-injection diesel engine was used to evaluate effects of blends of soy biodiesel and petrodiesel on engine performance. Several blends of soy biodiesel and petrodiesel were used in the experimental investigation. The study revealed engine thermal efficiency was influenced by biodiesel blends and the amount of biodiesel in the blend. Improvement in engine thermal efficiency was observed when the biodiesel in the blend was below 50%. Best efficiencies were achieved when the blend contained between 20 and 30% of biodiesel. Operating the engine on biodiesel incurred some penalty in engine power output, up to about 3% at rated speed.

Soy biodiesel had distinct advantage in reducing exhaust hydrocarbons and particulate matter (measured as smoke levels) but emissions of oxides of nitrogen increased as the content of biodiesel in the blend was increased. There is possibility that biodiesels may not be very stable when stored for a long period of time or when subjected to changing temperature or exposed to atmosphere. This may influence their physical or chemical properties or both which could impact engine performance. More study is needed to investigate stability of biodiesels and their blends if blends containing higher concentration of biodiesel are to be promoted to reduce dependency on petroleum based diesel.

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1. Background

There has been considerable interest in using alternate fuel to power current internal combustion (IC) engines. Fuels used in diesel engines require different characteristics than those used in spark ignition engines. The most attractive fuel for diesel engines, as a diesel fuel substitute, is biodiesel (also called as biodiesel fuel). The base feedstock for biodiesel varies depending on countries and regions. The most common feedstock used to make biodiesel in the U.S. is soy oil because of its availability and cost advantage over other feedstocks. The soy vegetable oil is allowed to react with alcohol, such as methyl or ethyl alcohol in the presence of a catalyst. The resulting product, after some processing steps, is transesterified soy oil (called methyl or ethyl ester of soy) called biodiesel. Soy biodiesel has physical and chemical properties that are closer to those of petroleum based diesel (petrodiesel) than some of the other fuels considered as candidates for diesel engine application. In general, the viscosity of biodiesel is higher while the mass-based energy content is lower than those of petrodiesel, as shown in Table 1. Biodiesels contain oxygen embedded in their structure. While the lower specific energy content of biodiesel could impact power developed by the engine, the higher viscosity would influence fuel spray characteristics and hence fuel distribution and mixing in the engine combustion chamber. Biodiesels also contain oxygen in their fuel structure while petrodiesels generally are void of any oxygen. This and the fuel distribution would impact combustion of the mixture and which could impact engine power output and exhaust emissions. While several studies have been conducted to evaluate power output and exhaust emissions of a diesel engine when operating on biodiesel fuels, the results have shown wide divergence making it difficult to infer the effects of biodiesel more on exhaust species and, to a lesser extent, on power output [1-6].

While there are many unanswered questions about the use of soy biodiesel and its blends in diesel engines, this project was conducted to address only two topics of interest, namely the effects of using soy biodiesel and its blends on power output and engine-out exhaust emissions. Consumers would be more receptive to using biodiesel in their diesel engines if they knew how the new fuel would impact their engine performance. It was also of importance to assess if any particular blend would perform superior to other blends or pure soy biodiesel.

The experimental work was conducted on a single cylinder, direct-injection (DI) diesel engine. DI diesel engines are being considered to be more important than the indirect-injection (IDI) engines because their potential to achieve higher thermal efficiency than IDI engines.

2. Objectives

This project was undertaken with two major objectives:

- a. Is there a penalty in engine power output when a DI diesel engine is operated on soy biodiesel or its blends with petrodiesel?
- b. Are there any environmental benefits, in the form of lower levels of exhaust emissions, when soy biodiesel or its blends are used in a DI diesel engine?
- c. Is there an optimum blend of soy biodiesel and petrodiesel that leads to improved engine performance when compared with petrodiesel?

To address these issues, an experimental study was conducted, under controlled conditions, using different blends of soy biodiesel and petrodiesel.

3. Experimental

A single-cylinder, water-cooled, naturally aspirated DI diesel engine was used in the experimental work. The engine was naturally aspirated and has a compression ratio of 18.5:1. The engine specifications are given in Table 2. The engine was connected to a water-brake dynamometer for loading purposes. A precision pressure-controlled system was incorporated in the water line to avoid fluctuations in the load carrying capacity of the dynamometer. A strain gage type load cell was used to measure load and hence engine torque. Figure A1 (Appendix A) shows the engine set up.

Table 1
Properties of Fuels Used in the Engine

Fuel	Density, kg/m ³ at 22 C	Viscosity, cP at 22 C	LHV, MJ/kg	LHV, MJ/liter **	Cetane Number
B0	850 [*]	2.60 [*]	42.2 ⁺	35.9	42 – 44 ^{**}
B20	856 [*]	2.76 [*]	41.25 ^{**}	35.3	43-45 ^{**}
B50	865.5 [*]	3.33 [*]	39.8 ^{**}	34.4	45-48 ^{**}
B100	881 [*]	4.19 [*]	37.6 ⁺	33.9	49 – 52 ^{**}

^{*} Measured

⁺ From supplier

^{**} Estimated

Several sensors were used to measure temperature of inlet air and exhaust gases, air flow rate into the engine, and temperature of coolant in the engine. The fuel flow into to the engine was measured by a volumetric system. This technique provided more accurate data than an electronic fuel flow sensor system. A wide-range exhaust oxygen sensor, calibrated for the fuel, was used to monitor air-to-fuel (A/F) ratio used in the engine. Figure A2 (Appendix) shows some of the instrumentation associated with the engine set up.

Samples of exhaust gas were withdrawn about 300 mm downstream of the exhaust manifold and were analyzed for carbon monoxide (CO), hydrocarbons (HC), nitric oxide (NO), oxides of nitrogen (NOx) and particulates (PM). A Bosch Smoke meter was used to determine particulate concentration in the form of Bosch Smoke No (BSN). The exhaust sample line was heated and maintained at about 110 C to reduce condensation. The concentration of CO was measured by using a non-dispersive infrared analysis technique while flame ionization detection (FID) system was used to measure HC concentration. NO and NOx were measured by using a chemiluminescent analyzer. The analyzers were calibrated before and during tests.

Samples of exhaust particulates were collected at periodic intervals during each test run. A recommended filter paper was used to collect the samples. The sample line between the engine exhaust and the Bosch Smoke metering system was heated and maintained between the temperature of 130 C and 150 C. The samples were analyzed using a Bosch analysis equipment which was calibrated during the process.

Table 2
Engine Specifications

Bore (mm)	78
Stroke (mm)	80
Displacement (l)	0.382
Compression ratio	18.5:1
Rated speed (rpm)	2400
Maximum torque speed (rpm)	1800

The fuels used in the tests were low sulfur diesel No.2 (petrodiesel) containing 15 ppm of sulfur, soy biodiesel, and blends of the two fuels. The blends were prepared in advance and were allowed to remain in the tank for at least 48 hours before using them in the tests. Several tests were conducted to compute statistical averages of the engine performance parameters and reduce variability in test data. Tests were conducted at two engine speeds: the rated speed of 2400 rpm and 1800 rpm, the speed at which the engine produced maximum torque.

4. Results and Discussion

Although several blends of petrodiesel and soy biodiesel were used in the project, the results section will dwell on the following fuels: pure petrodiesel (B0), a blend of 80% petrodiesel and 20% biodiesel (B20), a 50-50 blend (B50), and pure soy biodiesel (B100). The other blends used were 90% petrodiesel and 10% biodiesel (B10) and 70% petrodiesel and 30% biodiesel (B30). The percentages of the fuels are based on volume percent of each individual fuel in the blend.

Table 3
Engine Power Difference with Biodiesel

Fuel	1800 rpm	2400 rpm
B0	1	1
B50	- 1.7%	-1.5%
B100	- 3.1%	- 2.9%

4.1 Effects of fuel on engine power output and efficiency

The engine used in the experiments had an overload fueling system to produce additional power to respond to transient load conditions. It was therefore difficult to evaluate the impact of biodiesel on power output of the engine without using a range for the variations.

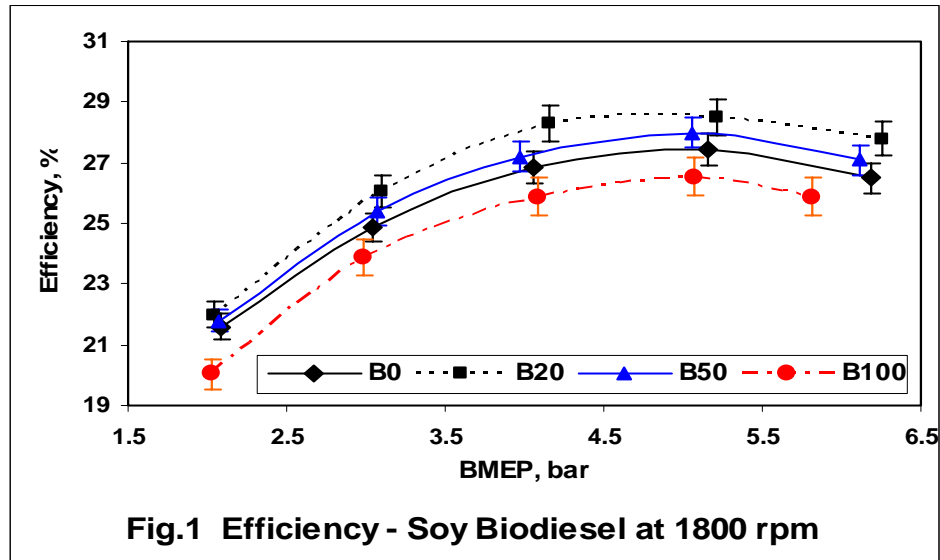
This range was estimated from A/F ratio and measured flow rates of the fuel. Table 3 shows power differences obtained at the two test speeds when the engine was fueled on B50 and B100. Operating the engine on pure soy biodiesel reduced power by about 3% at the rated speed compared to the operation on petrodiesel. On volumetric basis, soy biodiesel contains about 5.6% less energy than that of the petrodiesel. But biodiesel has higher viscosity than petrodiesel, as shown in Table 4. Since the fuel pump of the single-cylinder engine metered fuel on volume basis, the effect of lower energy content and higher viscosity will influence fuel delivery to the

engine and hence energy supplied. The measurement of fuel flow rate showed a small increase in biodiesel fuel delivery at the rated speed in comparison to petrodiesel. This will impact thermal efficiency of the engine.

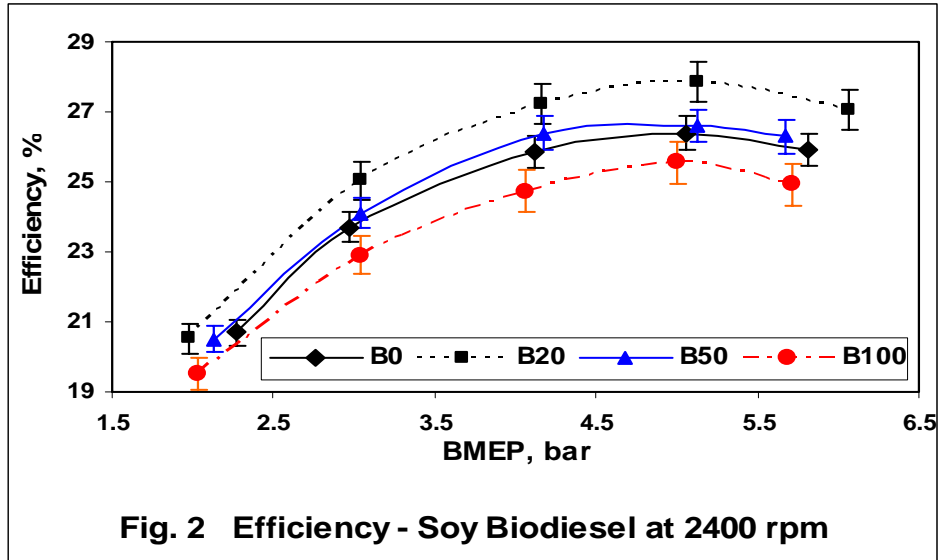
Table 4
Viscosity of Fuels and Blends (measured)

Temperature	Diesel	B50	B100
4.5 C	4.47 cP	6.35 cP	7.77 cP
22 C	2.60 cP	3.33 cP	4.17 cP
29.4 C	2.26 cP	2.69 cP	3.26 cP
37.8 C	1.74 cP	2.15 cP	2.74 cP

Figures 1 and 2 show thermal efficiency of the engine Vs engine load, in the form of brake mean effective pressure (bmep), when operated on different fuels at 1800 rpm and 2400 rpm, respectively. The engine thermal efficiencies with B10 and B30 fuels are omitted in the figures for clarity purposes.



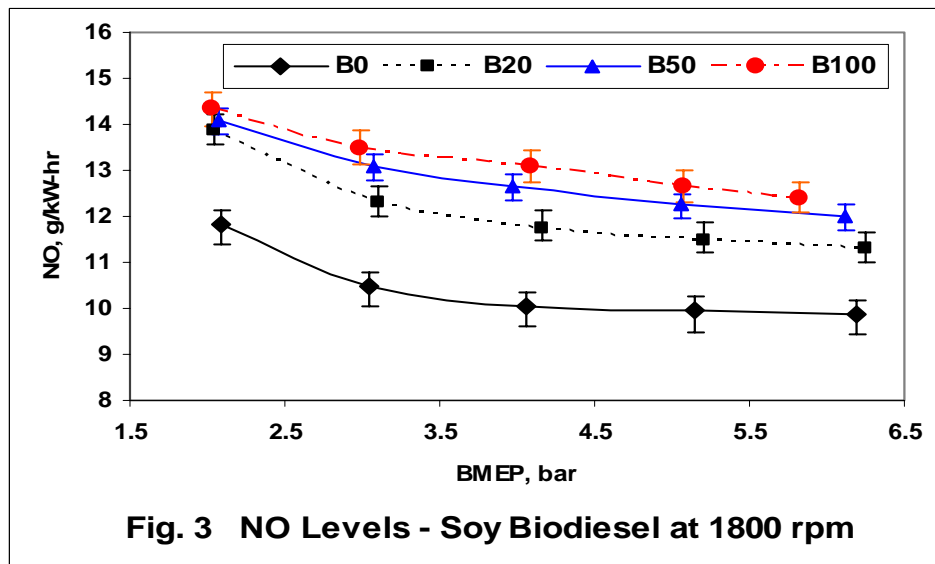
The engine thermal efficiency, relative to petrodiesel, increased as the content of biodiesel in the blend increased between 20% and 30%. Further increase in biodiesel content reversed the trend resulting in lower thermal efficiency, as shown in the figures. The addition of a small amount of biodiesel to the blend improved fuel lubricity thereby reducing frictional losses which could have contributed to improved efficiency. Furthermore, the presence of embedded oxygen in the biodiesel molecule could also contribute to improvement in combustion, particularly in fuel-rich zones in the combustion chamber.



The series of tests conducted with the same fuel or blend showed variations in thermal efficiency of as much as 5%. The thermal efficiency values were the highest with B20 and B30 fuel blends. The difference in the values between B20 and B30 were insignificant, within 0.7% of each other over most of the load range.

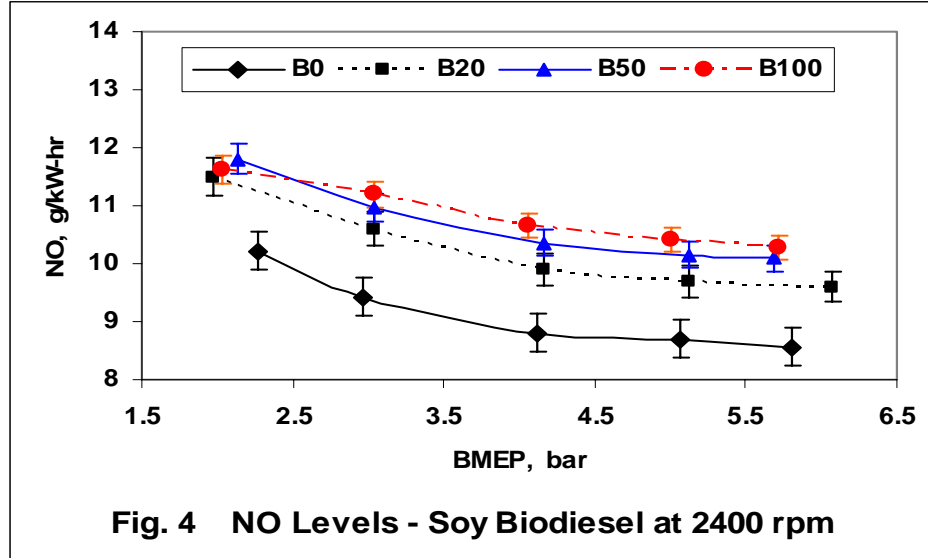
4.2 Effects on emissions

Several studies have pointed out that biodiesel fuels produce higher levels of nitric oxides (NO) and NO_x than petrodiesel when the engine is operated at same speed and load. However, there is discrepancy as to the degree of increase in the levels of NO or NO_x produced by biodiesel fuels.

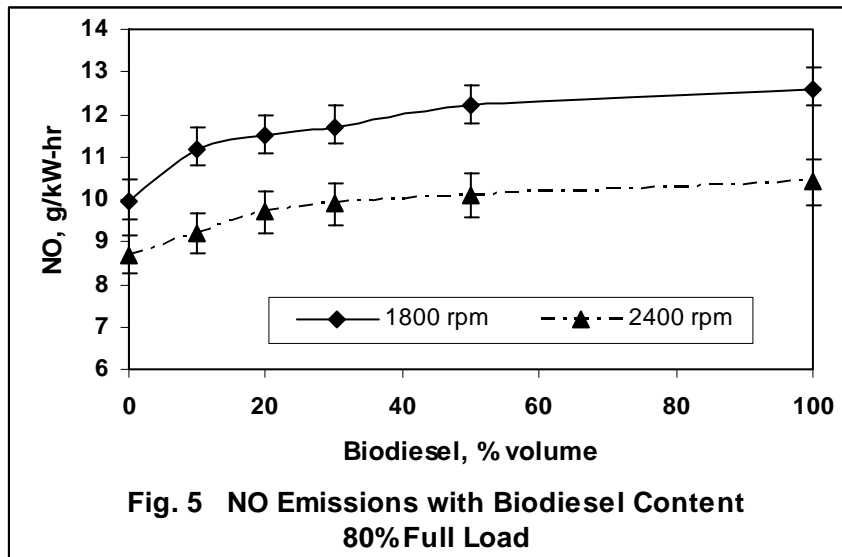


Figures 3 and 4 show NO emissions at 1800 and 2400 rpm, respectively, as the load was increased from light to about 100%. Clearly, petrodiesel produced the lower specific NO than

any of the biodiesel blends. Adding 20% of soy biodiesel to petrodiesel increased specific NO by as much as 20%. NO levels increased as the content of biodiesel in the blend increased but the increase was nonlinear, as shown in the figure. In fact, operating the engine on B100 increased NO levels by about 35 to 40% over the petrodiesel NO levels.



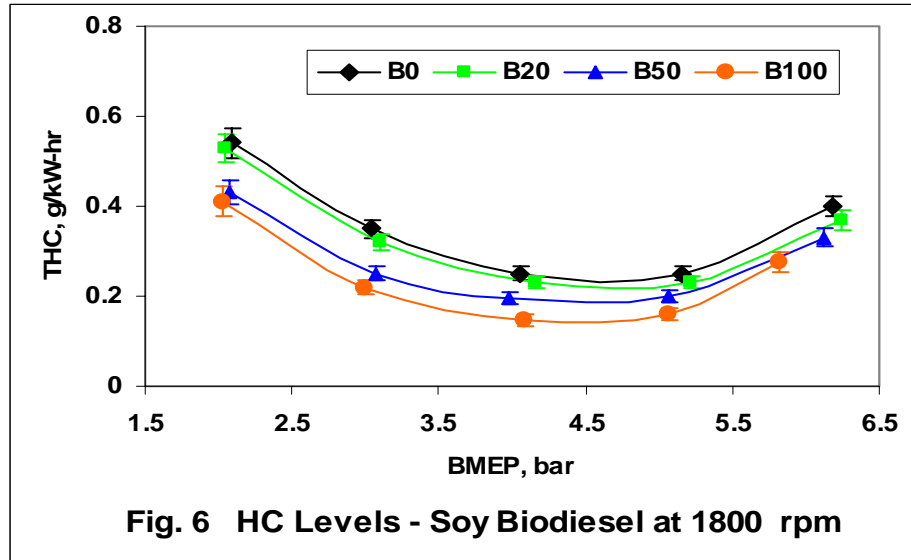
NO levels at 2400 rpm were lower than the corresponding levels at 1800 rpm due to shortened real time that affects NO formation and decomposition during combustion and expansion processes in the cylinder. But the trends in NO levels at both the speeds were similar. The absolute values of NO, in ppm, increased with an increase in engine load due to an overall temperature increase and the effects of overall A/F ratio but the specific levels decreased as the load increased.



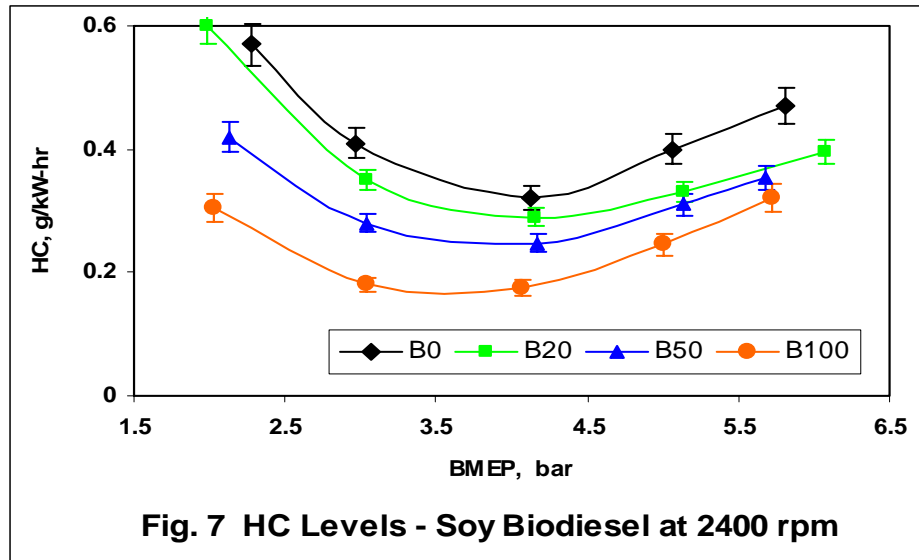
Some of the earlier investigations found similar trends in NO and NO_x, as shown in Figures 3 and 4 [7, 8] but others have reported lower emissions when using biodiesel blends [9, 10]. In his

investigation, Tat [10] discussed some of the issues that have led to lower emissions of NO_x from biodiesel fuel. There are strong reasons to believe that testing method (steady state on a dynamometer Vs transient testing on a chassis dynamometer), type of engine (older Vs newer engine), type of fuel system, and fuel chemistry influence NO_x emissions from a biodiesel fueled engine relative to petrodiesel fueled engine. It has been claimed that higher bulk modulus of biodiesel and vegetable oils leads to advanced fuel injection timing relative to petrodiesel. The advanced timing would increase residence time of high temperature gases in the cylinder and would yield higher NO_x emission. But measurements of injection timing reveal the advance was small, of the order of one or two crank angle degrees [10]. This, by itself, cannot explain the increases in NO levels observed in figures 3 and 4. There is no doubt that NO_x levels tend to increase when a DI diesel engine is operated on biodiesel or its blends in newer engines. The extent of NO_x increase would depend on the type of diesel engine utilized, its fueling system design, operating conditions, and properties of biodiesel or its blends.

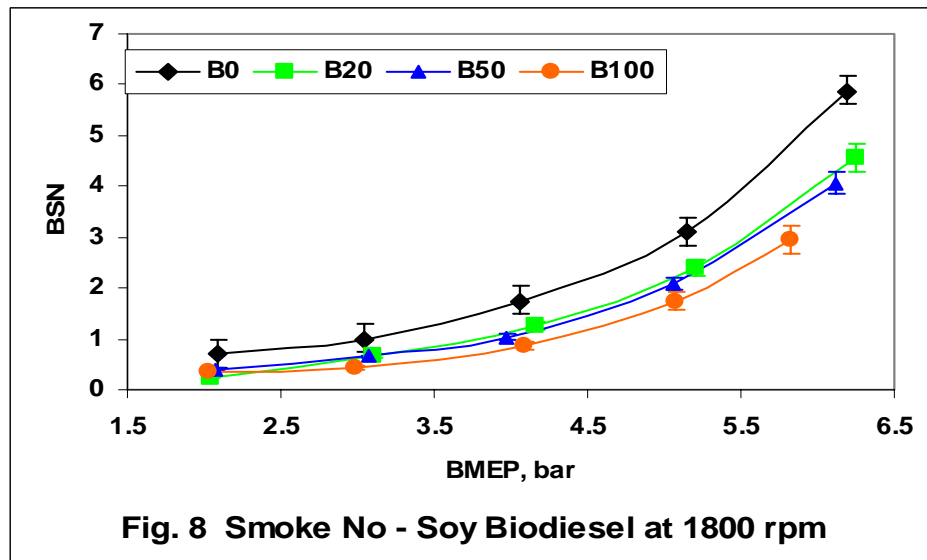
Figure 5 shows the effects of biodiesel content in the blend at 1800 and 2400 rpm when the engine was operated at about 80% full load.



From emissions consideration, soy biodiesel produced lower hydrocarbons (HC) emissions than the base fuel, petrodiesel, as shown in Figures 6 and 7. As biodiesel content in the blend increased, the levels of HC decreased. The overall A/F ratio at light loads is much leaner than the stoichiometric A/F. Furthermore, the dispersion of fuel and its mixing with the cylinder air further leans the mixture, particularly in zones that are father away from the injector tip. The very lean mixture would not burn completely or may continue to burn late in the expansion stroke resulting in increased HC emissions than in the mid-load range. At high loads, the local A/F ratio is generally richer than stoichiometric, leading to increased hydrocarbon production and emission. The use of B100 reduced HC levels by up to 33% at 1800 rpm and 45% at 2400 rpm relative to petrodiesel.



A major advantage of using biodiesel blends is the reduction in particulate levels emitted by the engine. Figure 7 shows exhaust smoke levels, measured in Bosch smoke Number (BSN), at 1800 rpm when the engine was fueled on different fuels. The solid particulates that make up smoke require an involved filtering system to clean exhaust of particulates. Reducing particulate levels provide an opportunity to reduce the size of the filtering device and hence aftertreatment system cost reduction. Even a small amount of biodiesel (10 to 20%) in the blend reduced smoke levels by over 20%. But the major impact is realized when B100 was used in the engine; at full load the reduction in BSN was as much as 45%.



Similar trends were observed at 2400 rpm (Figure 9). As engine speed increases there is less time for the fuel to mix with the air and undergo combustion. The reduced time, combined with an increase in fuel supply and richer A/F ratio in local zones, produced increased smoke levels at 2400 rpm relative to 1800 rpm.

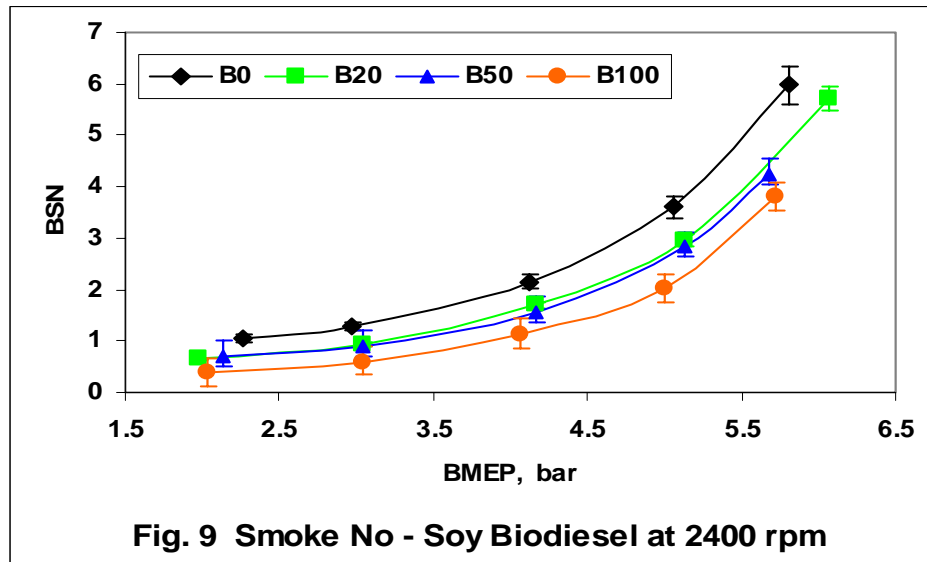
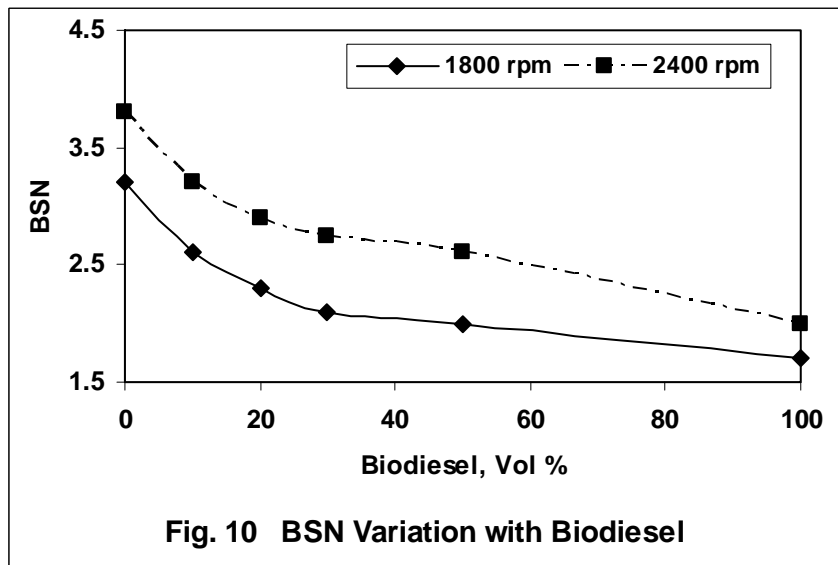


Figure 10 shows variations in smoke levels as biodiesel content in the blend was varied. The impact of increased biodiesel content on smoke levels can be clearly observed. A major advantage of biodiesel is its ability to lower smoke and particulate emissions from diesel engines. The extent of reduction depends on chemical properties of biodiesel which, to some extent, depends on feedstock and process used to make the fuel.



There are concerns that biodiesels in general, and soy biodiesel in particular, may not be very stable over a prolonged period of time or when subjected to temperature variations or exposure to air. That possibility exists because the fuel may undergo changes in its physical properties and/or chemical composition. Furthermore, the blend may not remain in homogeneous form for a long period of time. Most of the blends, including those that were used in the present study, were prepared by splash blending of ultra-low sulfur diesel (No 2) and soy biodiesel without the use of

any stabilizer. Although not part of the present study it is of interest to us and biodiesel users if engine performance suffers due to possible instability of biodiesel blends. Time and funding limitations did not permit us to investigate stability of the blends and its impact on engine performance. The present work, however, did consider technical details of blend homogeneity and if there are any indications of phase separation.

But we did measure blend viscosities after the subjecting the blends to temperature variations. The blends were prepared by splash blending and allowed to stand in their container for at least 2 days. The blend samples were then subjected to a temperature of 4.5 C for two days after which they were brought to room temperature of 22 C and allowed to stand in their test containers for another 48 hours. The viscosities of the test samples were measured to assess any observable changes in viscosities that may occur due to separation. Table 5 shows differences in viscosities when the mixed sample was compared with the sample from the top layer of the blend. Small differences in viscosities, of the order of 1 or 2% can be observed due to variations in tests, data recording, etc. but large variations of 3% or higher are generally caused by differences in fluid properties.

Table 5
Viscosity Variations

Temperature, C	Condition	B0, cP	B50, cP	B100, cP
4.5	Before Mixing After Mixing	4.52 (+1.1%) 4.47	5.78 (-8.2%) 6.3	7.61 (-2.2%) 7.78
22	Before Mixing After Mixing	2.63 (+1.5%) 2.59	3.24 (-2.7%) 3.33	4.19 (0.3%) 4.18
29.5	Before Mixing After Mixing	2.26 (0.9%) 2.24	2.61 (-3%) 2.69	3.24 (-0.6%) 3.26
37.8	Before Mixing After Mixing	1.85 (+5.1%) 1.76	2.19 (+1.8%) 2.15	2.7 (-1.1%) 2.73

It is worth noting that B50, a blend of 50% soy diesel and petrodiesel, had the largest differences in viscosities, particularly at temperatures of 29 C and below. It is not clear if this difference is due to changes in physical properties caused by some type of phase separation or partial separation or chemical or both. But it is interesting that the blend did experience some change which could impact characteristics of fuel injection, mixing and hence combustion process. More detailed investigation is further warranted.

5. Conclusions

This work was conducted to evaluate performance of a DI diesel engine when operated on blends of soy biodiesel and petrodiesel. The study reveals:

- There is some penalty in engine power output when biodiesel and its blends are used to operate the engine. The penalty depends on the type of fuel system, type of engine used

in the tests and procedure used to test the engine. In a DI diesel engine with a pump-plunger type mechanical fuel injection the reduction in power output at the rated speed was as much as 3.2%.

- Using biodiesel blends yielded higher thermal efficiency up to a point. Further increasing biodiesel content resulted in reducing efficiency of the engine relative to petrodiesel. The blends containing between 20% and 30% biodiesel produced the highest efficiency of all the blends. The engine was not as efficient as a petrodiesel engine when B100 was used.
- Both HC and smoke decreased as biodiesel content in the blend increased but the presence of even a small percent of biodiesel (such 10 to 20%) reduced smoke levels by as much as 18 to 24%. Likewise, HC levels were consistently lower when biodiesel blends were used.
- Biodiesel operation produced higher NO emissions than the corresponding petrodiesel operation. NO levels increased by about 20% when the fuel was switched from petrodiesel to B100. The increase was lower for lower concentrations of biodiesel.
- There are concern that biodiesel may not be very stable when stored for a prolonged period of time or when subjected to temperature variations or exposure to air. Measurement of blend viscosities raises concern that biodiesel blends may not show consistent properties which could possibly impact engine performance. More detailed investigation is needed to address these issues.

6. Recommendations

More extensive work is needed to investigate stability of biodiesel and its blends in a DI diesel engine and its impact on engine performance. There is also a need to consider soy biodiesels obtained from different feedstock and evaluate how the base feedstock influence physical and chemical properties of the fuel and how it impacts fuel stability and engine performance. Finally, different types of fuel systems should be used to assess if fuel system design and operation have any effects of engine behavior.

7. References

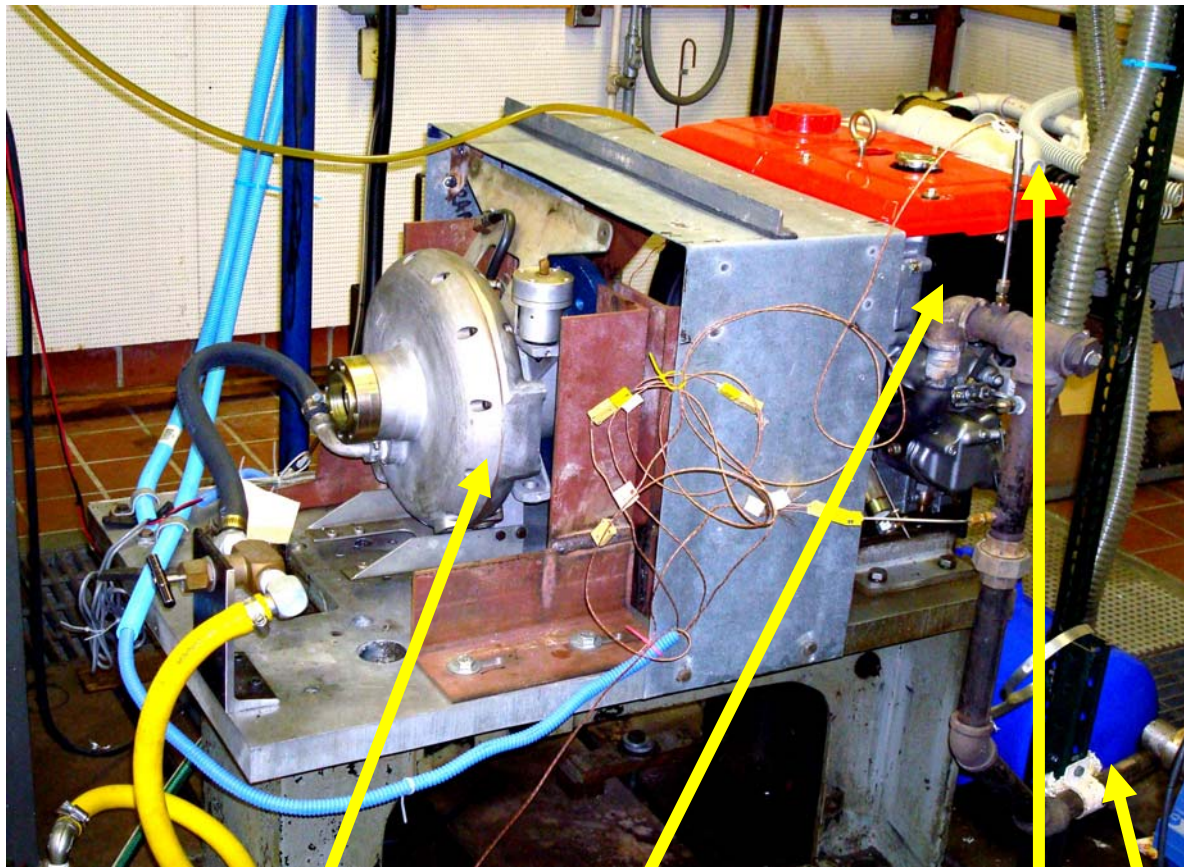
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8. Nomenclature

bmeP	Brake mean effective pressure in bar
BSN	Bosch Smoke Number (no-dimensional)
cP	Viscosity of the fuel in centipoise (1 cP = 1 mPa-s)
Efficiency	Thermal efficiency (= power out/fuel energy in)
HC	Unburned hydrocarbons (total hydrocarbons)
Ultra-Low Sulfur	Diesel fuel containing maximum 15 ppm of sulfur
NO	Nitric oxide
NO _x	Oxides of nitrogen (mostly NO and NO ₂)
PM	Particulate matter (mostly smoke but may include other solid particles)

APPENDIX A



Dynamometer **Engine** **Air Flow Measurement** **Surge Tank**

Figure A1. The Engine and Dynamometer Set Up

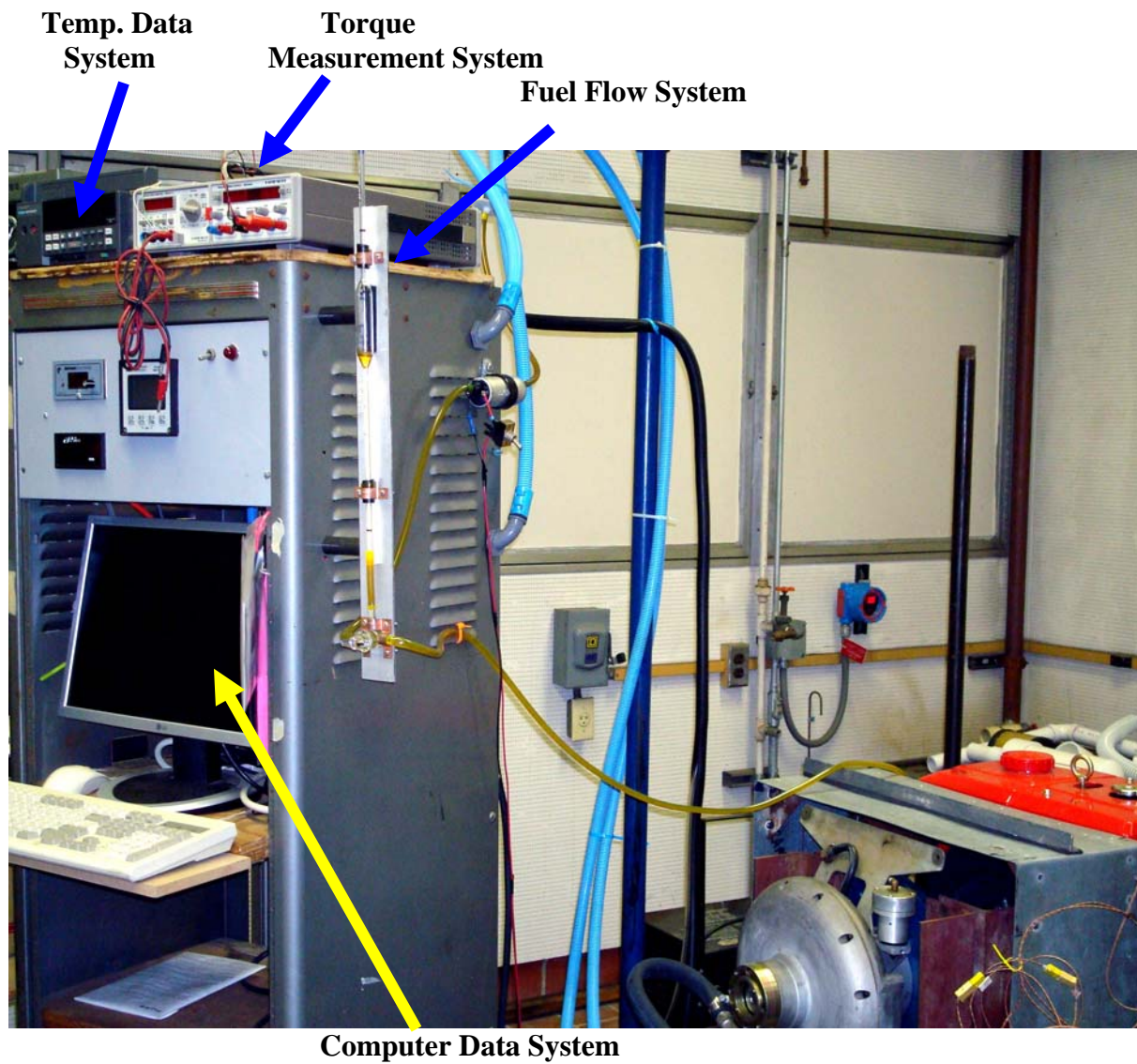


Figure A2. Measurement and Data Collection